https://doi.org/10.31891/2219-9365-2023-73-1-11
УДК 621.396.969.1

Yevhen VISTYZENKO
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
https://orcid.org/0000-0003-4394-7264
e-mail: yevhenchs@gmail.com
Andriy MOVCHANYUK
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
https://orcid.org/0000-0003-2901-0424
e-mail: movchanuk@rtf.kpi.ua
Mykhailo STEPANOV
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
https://orcid.org/0000-0001-6376-4268
e-mail: 2m.stepanov@gmail.com
Juliy BOIKO
Khmelnytskyi National University
https://orcid.org/0000-0003-0603-7827
e-mail: boiko_julius@ukr.net

# SEISMIC WAVE RECORDER DESIGN FOR DEVELOPMENT FOOTSTEP HUMAN DETECTION ALGORITHMS

*The article shoving the results of development seismic signal recorder for purpose of registration human footstep seismic signals. Design of recorder was adopted for collection seismic signals and store it on PC, for next seismic signal processing and creation signal detection and classification algorithms.*

*The article provides an overview of the types of seismic waves, their classification is given. The conditions for the propagation of seismic waves are determined, and the features of Rayleigh waves are clarified. The design structure of the seismic sensor has been developed. The specifics of the functioning of the seismic sensor are described, the place and conditions of power supply and placement of the external interface are recognized. The specifics of using the sensor of an electromechanical transducer - geophone and the features of measurements using a stationary earth are described. It is shown that the development of a seismic signal sensor circuit implies the placement of input amplifiers in its structure. The main amplitude-frequency and phase-frequency characteristics of the geophone are presented. Geophone equivalent circuit, amplifier circuit, low-pass filter circuit are presented. Illustrations of types of seismograms are given, recommendations on the features of digital signal processing are given. The order of seismic signal processing is connected with its transmission from the sensor through the amplifying stage, passing through a low-pass filter in order to minimize noise and interference. The next step is to send a signal to the ADC. From the presented graphs of sensitivity and phase shift of the geophone, it follows that special attention should be paid to the curve corresponding to the sensor with an open output. This configuration of the sensor is optimal in the context of the formation of the maximum equal frequency response.*

*As papers result was proposed structural and schematic design for all main recorders blocks and software features that required for properly using recorder. Tests in real conditions on test sites have shown the correctness of the choice of schemes of technical solutions for the task of registering seismic waves.*

*Keywords: seismic signals, autonomous seismic sensors, geophone, signal recorder*

Євген ВІСТИЗЕНКО, Андрій МОВЧАНЮК, Михайло СТЕПАНОВ
Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського»
Юлій БОЙКО
Хмельницький національний університет

# ПРОЄКТУВАННЯ РЕЄСТРАТОРА СЕЙСМІЧНИХ ХВИЛЬ ДЛЯ РОЗРОБКИ АЛГОРИТМІВ ВИЯВЛЕННЯ КРОКІВ ЛЮДИНИ

*У статті наведено результати розробки реєстратора сейсмічних сигналів для реєстрації сейсмічних сигналів кроків людини. Конструкція реєстратора була адаптована для збирання сейсмічних сигналів та збереження їх на персональний комп'ютер, для подальшої обробки сейсмічних сигналів та створення алгоритмів виявлення та класифікації сигналів.*

*В результаті роботи було запропоновано структурно-схемні рішення всіх основних блоків реєстратора та програмні можливості, необхідні для коректного використання реєстратора. Випробування у реальних умовах на полігонах показали правильність вибору схем технічних розв'язків вирішення задачі реєстрації сейсмічних хвиль.*

*Ключові слова: сейсмічні сигнали, автономні сейсмічні датчики, геофон, реєстратор сигналів*

## Statement of the problem in general form and its connection with important scientific or practical problems

Seismic alarm systems are currently one of the most promising technologies for detecting the violation of the boundary of the protected area.

The principle of operation of seismic signaling systems is based on the detection and registration of vibrations that occur in the soil during human footstep on the surface of the earth. Sensors are installed in the soil at a small depth and convert seismic vibrations into electrical signals.

The development of modern microelectronics makes it possible to process the collected signals directly on the sensor. To develop algorithms for processing seismic signals, it is necessary to have a large number of recordings of seismic waves under controlled conditions. Commercially available seismic recorders are designed to record seismic waves for the purposes of geological exploration or earthquake detection. They are poorly adapted to the tasks of recording signals excited by human steps and have a high cost.

In this work, a version of the architecture and schematic implementation of a stand for recording seismic waves is presented, which can serve for the task of recording human steps, vehicle traffic, and seismic noise.

## Analysis of studies and publications

A seismic wave is a periodic displacement of the constituent parts of the soil from its equilibrium position. With any impact on the surface, a whole ensemble of seismic waves arises in the soil, which are usually classified according to the direction of oscillation of the particles relative to the direction of propagation of the wave front. According to the classification, the following are distinguished:

- primary waves (P - waves),
- secondary waves (S - waves),
- Rayleigh waves,
- Love waves.

Primary and secondary waves fade slightly with increasing depth, which causes their uniform distribution in three spatial coordinates. Primary and secondary waves are successfully used in earthquake analysis, mineral exploration and geophysical research.

Unlike primary and secondary waves, for the existence of which an isotropic space is sufficient, for the occurrence of surface waves (Love, Rayleigh) a necessary condition is the presence of two media with different physical properties in contact. An example of two such media can be the soil and the atmosphere, or a metal plate and water on its surface.

It should be noted that the trajectory of particle movement during Rayleigh wave propagation is elliptical with the dominance of the vertical component. Surface waves are significantly attenuated with increasing depth, which leads to their propagation near the line of separation of two contacting media.

The energy of the source of seismic waves is unevenly distributed between different types of waves, namely: primary waves carry 7% of energy, secondary waves 26%, and Rayleigh waves 67% of energy [1].

An equally important parameter is the attenuation of the seismic wave amplitude depending on the distance to the excitation source. For a Rayleigh wave, the attenuation is proportional to $1/R$, where $R$ is the distance to the wave excitation source. At the same time, primary and secondary waves are attenuated in proportion to $1/R^2$ [2]. It is this feature of Rayleigh waves that allows them to be used in seismic alarm systems.

## Presentation of the main material

In this chapter, we will review the design of a seismic sensor. Separately, the structure of the sensor will be presented, the geophone and components of the sensor circuit will be described: amplifier, filter, ADC, software.

a. Sensor structure.

The recorder (Fig. 1) had the following requirements: recording and saving of seismic wave signals (primarily Rayleigh waves), the ability to set the gain of the amplifier, transfer of recorded signals to a PC for further storage.

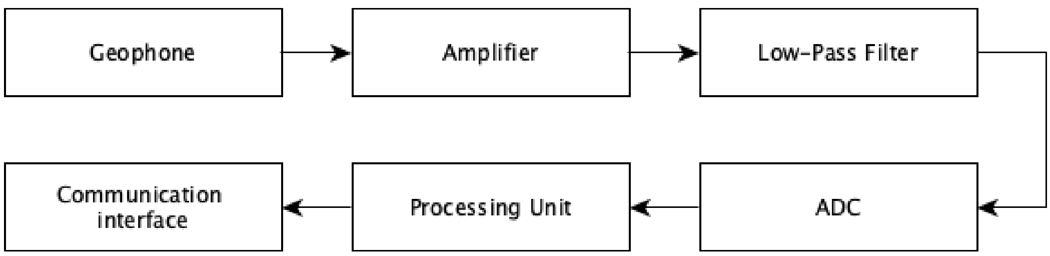



**Fig. 1. The structure of the scheme of the seismic signal recorder**

According to the selected structural scheme, the seismic signal received by the sensor is fed to the amplifier to ensure the required signal level. The amplified signal is then passed through a low-pass filter to prevent spectral overlap and reduce noise. The filtered signal is fed to the ADC. The results of the transformation are fed into the computing core. The computing core records and processes data (detection and classification) received from the sensor and transmits them to the external interface. The USB 2.0 interface was used as an external interface. The power supply of the stand was organized from a separate battery to reduce the impact of noise from pulsed PC power sources.

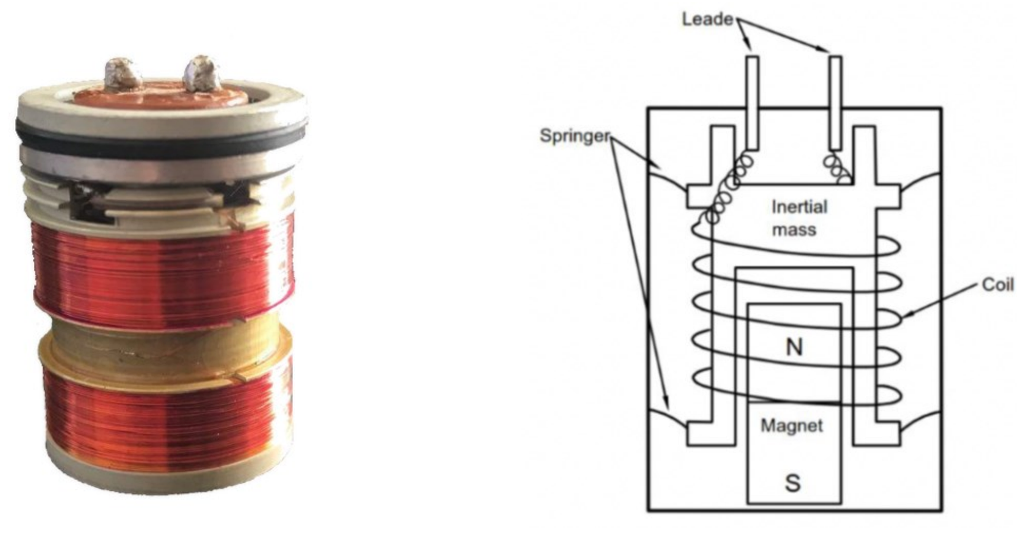
b. Geophone.

An inductive geophone was used as a sensor of seismic waves, as the most sensitive type of sensors.

A geophone is an electromechanical transducer for registering soil displacement. When registering the movement of the soil, it must be done relative to the "immovable" ground. It is almost impossible to ensure this condition, therefore geophones use an inertial mass suspended on a spring suspension to the body. When the soil moves, the mass maintains its position in space thanks to the spring suspension, and the body repeats the soil oscillations [3].

The principle of electromagnetic induction is used to convert mechanical vibrations into electrical ones. A cylindrical coil is used as a mass suspended on a suspension. Inside the coil is a permanent magnet attached to the body, which creates a radial magnetic field (Fig. 2b). When the soil shifts, the body of the geophone, together with the magnet, moves. At the same time, the coil remains stationary, because of which an emf is induced in the coil.

Structurally, the geophone consists of two counter-wound coils located in the magnetic field of a permanent magnet (Fig. 2a). This provides summation of the emf caused by the coil movement and subtraction of the emf induced by external sources to suppress common mode interference.




**а) б)**

**Fig. 2. а) – geophone without case; б) – a simplified scheme for geophone construction**

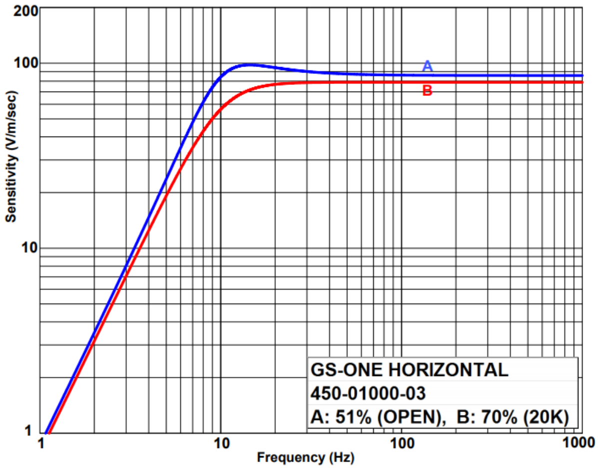
To ensure the uniformity of the transmission characteristic, the geophone coil is shunted with an additional resistance, the nominal value of which is usually specified in the documentation. This allows to reduce the unevenness of the characteristic. This is illustrated by the sensitivity graph (Fig. 3) of a typical Geospace GS-ONE geophone [4]. The graph corresponding to the unshunted coil is shown in blue, and the graph corresponding to the shunt is shown in red.

When developing equipment for receiving seismic signals, the greatest attention is paid to the input amplifiers, to which the inductive geophone is directly connected. Since, depending on the type of seismic survey, it is necessary to allocate certain ranges of input frequencies, if necessary, links of filtering and correction of the shape of the frequency response and frequency response of the geophone are added to the geophones. Therefore, the operation of the geophone should be considered in conjunction with the input cascades of the receiver of seismic waves.

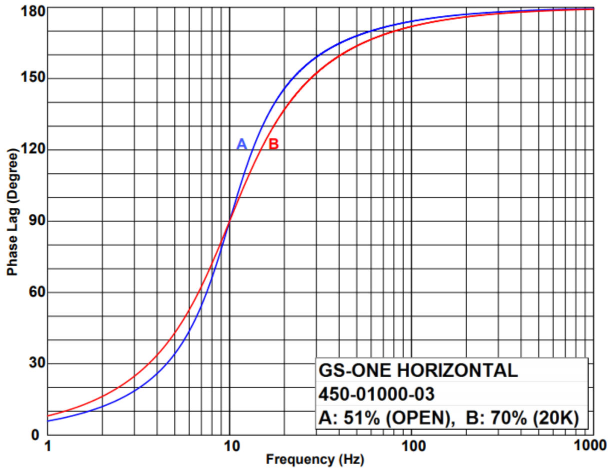
For speed and ease of development, engineers use SPICE systems for modeling electronic circuits. For the possibility of fully modeling seismic signal reception systems, taking into account the influence of parasitic parameters of the geophone's output elements, a method of calculating the geophone's replacement scheme was developed [5]. Geospace Technologies (USA) geophone GS-ONE was chosen as the sensor for the recorder.

The amplitude-frequency and phase-frequency characteristics of the GS-ONE geophone [4] are presented in the graphs (Fig. 3).

Special attention should be paid to the fact that two curves are shown on the sensitivity and phase shift graph of the geophone (Fig. 3). Curve A corresponds to a sensor with open outputs. Curve B, in turn, corresponds to the sensor with the addition of a shunt resistance of 20kΩ at the output. This configuration of the sensor is considered optimal, because it allows you to get the flat frequency response as much as possible.




**a)**




**b)**

**Fig.3. Graph a) – GS-ONE geophone sensitivity; b) – GS-ONE geophone phase lag**

An equivalent circuit for use in SPICE simulation packages is shown in Fig. 4. You can familiarize yourself with the method of calculating the parameters of all elements of the geophone replacement scheme in [5].

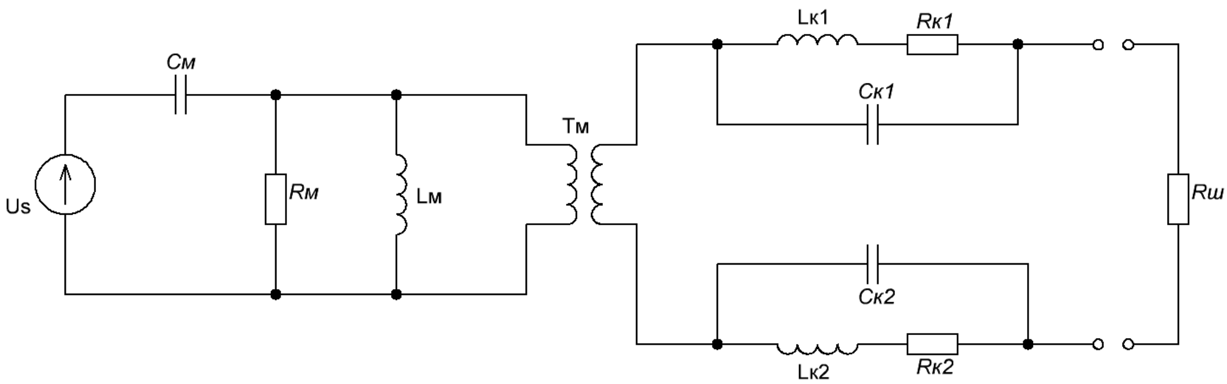



**Fig.4. Geophone equivalent circuit**

Components on the equivalent scheme: Rk, Ck – coil parasitic parameters, Rш – shunt resistance, which is added to the geophone to increase the damping factor and reduce the unevenness of the frequency response. $T_M$ – geophone gain $C_M$, $R_M$, $L_M$ – the mechanical properties of the geophone suspension.

c. Amplifier.

As a signal amplifier (Fig. 5), an instrumental operational amplifier INA129, manufactured by Texas Instruments [6], was used. The use of an instrumental amplifier is justified by the fact that it has a significantly higher suppression ratio of the in-phase signal, to which the geophone is very sensitive. For the selected model, it is 95 dB [6]. An additional convenience in using this type of amplifiers is the ability to adjust the gain using only one resistor. This is necessary due to the fact that the signals that will be recorded in the database will be received at different landfills, with different soils, and therefore, with different conditions of propagation of seismic waves. And this, in turn, may make it necessary to change the gain of the amplifire.

The developed circuit of the amplifier contains an anti-aliasing filter. Resistor R3 acts as a shunt resistance to ensure the recommended operating mode of the geophone.

Resistors R1 and R2 are necessary due to the inductive nature of the sensor. They shunt the input resistance of the operational amplifier and balance the currents at its input.

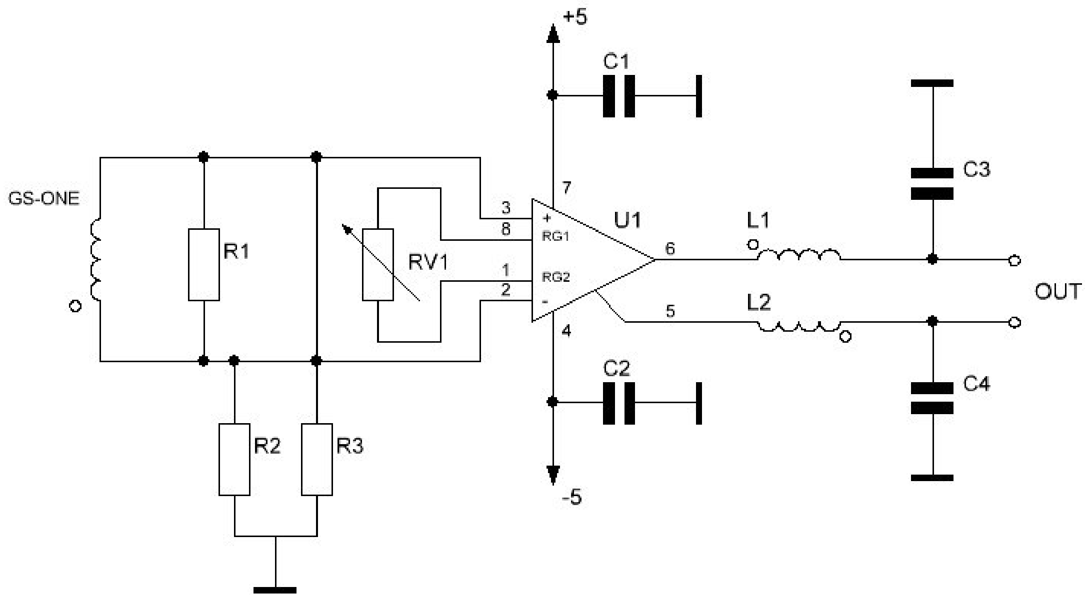



**Fig.5. Amplifier scheme**

d. Filter

After amplification, the signal from the geophone transfer to the low-pass filter. It performs two functions - an additional anti-aliasing filter and a limiter of the frequency range, in which the sensor characteristics are not normalized.

A low-pass filter located before the ADC reduces the effect of aliasing (overlapping), when continuous signals of different frequencies may overlap during signal discretization, which leads to the impossibility of separating them during further analysis.

It should be noted that the converting element in the geophone is an inductive coil, which can also work as a magnetic antenna. Therefore, when using a geophone without additional filtering of the signal at the input of the recording device, there will be a large number of noise frequency components that are more high frequency that range of seismic signals.

As the topology of the input filter, an active third-order Butterworth low-pass filter was chosen. The use of the Butterworth filter is caused by the need to obtain the most flat amplitude-frequency characteristic in the passband.

The third-order Butterworth filter provides attenuation of the signal outside the passband of −18 dB per octave, which is sufficient for practical use (this is confirmed by the results obtained during experiments). The bandwidth of the filter is 1kHz, which corresponds to the range of normalized characteristics of the selected sensor (GS-ONE).

The input filter is built on a precision low-noise operational amplifier OPA227 manufactured by Texas Instruments [7] (Fig. 6).

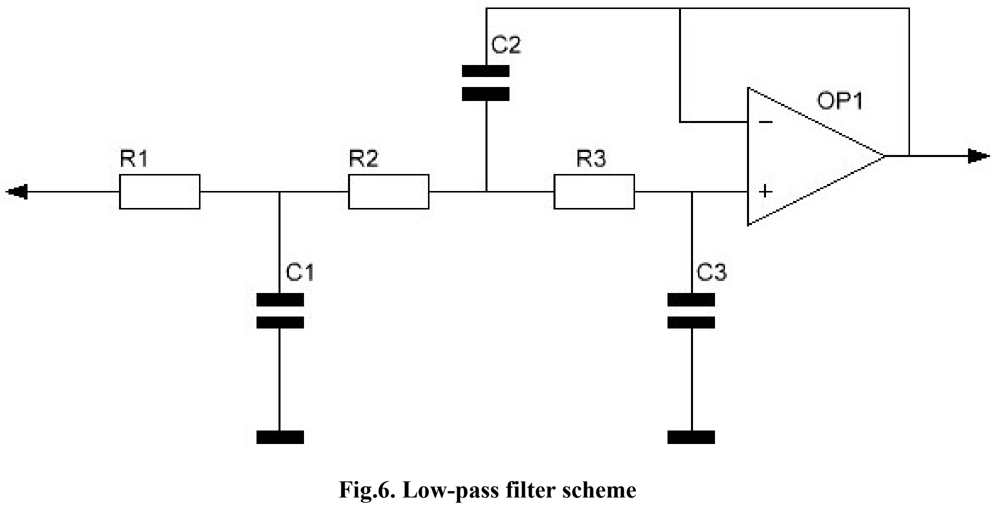



**Fig.6. Low-pass filter scheme**

The Saylen-Kaye scheme was chosen as the topology for constructing the filter. The main advantage of this topology is the use of an operational amplifier in buffer mode. This allows you to level the influence of the spread of the parameters of the operational amplifier

e. ADC

The main requirement for an ADC is its bit rate, which determines the dynamic range of the entire device. Seismic signals propagate in an environment with high attenuation, so when using a sensor to detect human steps, an increase in target detection range is achieved by increasing the dynamic range. In practice, 24-bit ADCs are most often used, the dynamic range of which is equal to 144dB.

The second, no less important parameter is the Effective Number of Bits (ENOB). It characterizes the quality of the digital signal. As an example, we can cite ADCs manufactured by Texas Instruments: ADS1246 and ADS1220. For our purposes, the sampling frequency should be equal to 2 kHz. For this value, the effective bit rate of ADS1246 is 18.5 bits [8], and ADS1220 is 17.33 bits [9]. As you can see, the actual effective bit rate can differ significantly, depending on the ADC model.

ADS1246 was chosen for the recorder.

d. Software

For processing and data storage was used laptop with installed MATLAB software.

To record and store the signals, in the MATLAB environment was developed software, which allow record the signal at the command of the operator and save it in an arbitrary place on the PC in the ".mat" format. This format is standard for storing data in the MATLAB environment. The file stores a data array consisting of two columns: the first has time stamps, the second has ADC readings. The user interface for this software is shown in Fig. 7.

The GS-ONE geophone was used as a sensor, complete with an amplifier circuit and a low-pass filter. The sensor with the amplifier and filter was mounted in a housing that was printed from ABS plastic and connected by a cable to the ADC board.

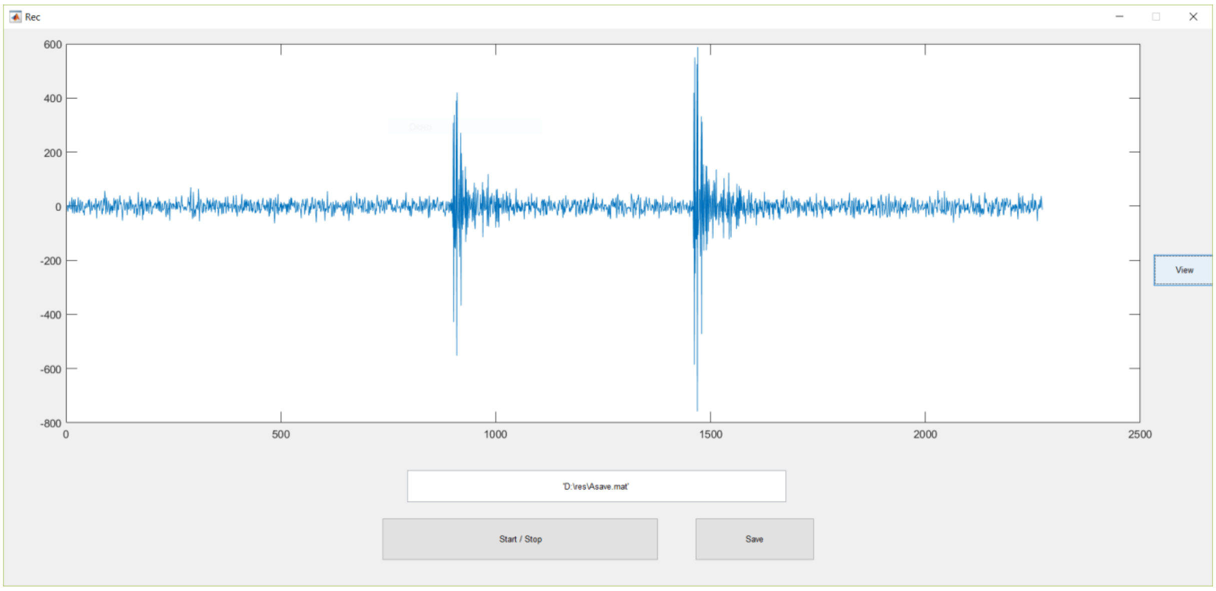



**Fig.7. Record software graphic user interface**

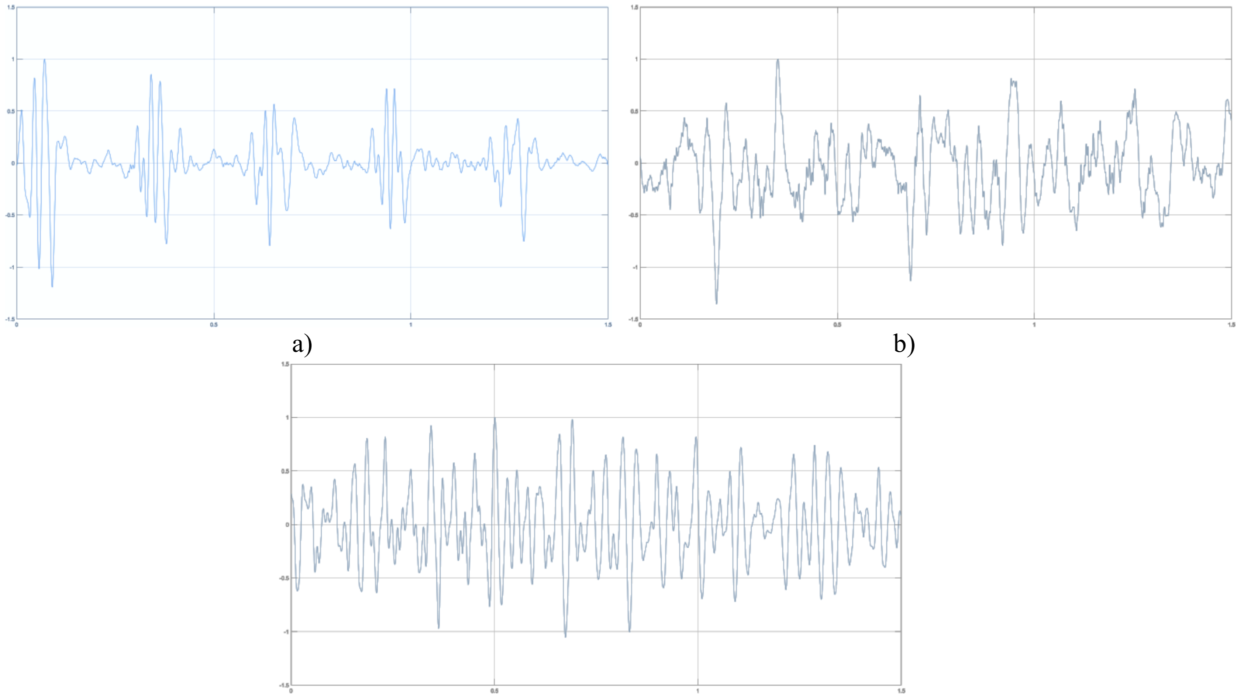
Consider signal dataset collection.

Figure 8 shows examples of seismograms recorded at test sites #1 and #2. Accumulation of records took place according to one scenario, during which passages of people were made at different distances from the sensor. Passages took place both individually and in pairs, at different speeds and by people of different weights. Recordings of the seismic background (noise) and the passing of a car at a certain distance from the sensor were also made.

Figure 8.a shows a seismogram of human steps lasting one and a half seconds, it has a clear periodic structure and a pronounced impulse character. The amplitude of the pulses fades when moving away from the sensor, this is clearly visible closer to the end of the displayed time interval.

Figure 8.b shows seismograms of the normalized noise background.

Fig. 8.c shows a seismogram taken during the passage of a passenger car. The appearance of the seismogram is very close to the noise one. The only difference is a sharper change in the amplitude of the signal caused by the approach/distance of the car from the sensor.



a) b)

c)

**Fig. 8. Examples of seismograms: a) – test site №1, human footstep;
b) – test site №1, seismic noise; c) – test site №1, car passing**

The signal processing for detection person in seismic alarm systems contain two main steps: detection of activity and signal classification.

For activity detection used different types of threshold detectors. Threshold detector does not require to use a height computation power and help to decrease quantity of classifications calculations.

For the second step used algorithms that can classify source of signal. As a good example of this types of algorithms is a decision tree or support vector machine. For both required to have set of features that will be generated from the signal. As a list of features can be used set of statistic characteristics of signals (dispersion, centroid, etc.) [10-13].

## Conclusions from this study and prospects for further development in this direction

Tests in real conditions on test sites have shown the correctness of the choice of schemes of technical solutions for the task of registering seismic waves. Further work will be carried out on the software component of the stand for better organization of the process of storing recorded data and adding opportunities for pre-processing signals directly during their recording.

## References

1. Miller G. On the partition of energy between elastic waves in a semi-infinite solid / G. Miller, H. Pursey, E. Bullard. // Royal Society London, Series A. – 1955. – №233. – C. 55–69. https://doi.org/10.1098/rspa.1955.0245.
2. Problems in seismic detection and tracking / [G. Succi, G. Prado, R. Gampert and other]. // Proceedings of SPIE - The International Society for Optical Engineering.. – 2000. – №4040. – C. 165–173. https://doi.org/10.1117/12.392572.
3. Anghelescu P. Human footstep detection using seismic sensors / P. Anghelescu, G. V. Iana, I. Tramandan // 2015 7th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), (Bucharest, Romania, 25-27 June 2015). – Bucharest : IEEE, 2015. P. AE-1-AE-2, https://doi.org/10.1109/ECAI.2015.7301179.
4. GS-ONE datasheet [Electronic resource] – Resource access mode: https://www.geospace.com/wp-content/uploads/GS-ONE-Geophone-4p.pdf.
5. Sushko, Y. V. Geophone Equivalent Circuit for Simulation Tasks in SPICE Packages / [I. O. Sushko, Y. V. Vistyzenko, A. V. Movchanyuk and other]. // Visnyk NTUU KPI Seriia - Radiotekhnika Radioaparatobuduvannia. – 2019. – C. 53–59. https://doi.org/10.20535/RADAP.2019.77.53-59.
6. INA129 datasheet [Electronic resource]. – 2015. – Resource access mode: https://www.ti.com/lit/ds/symlink/ina129-ep.pdf?ts=1631276970226&ref_url=https%253A%252F%252Fwww.google.com%252F.
7. OPA227 Datasheet [Electronic resource]. – 2015. – Режим доступу до ресурсу:https://www.ti.com/lit/ds/symlink/opa227.pdf?ts=1631452524432& ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FOPA227.
8. ADS124* datasheet [Electronic resource]. – 2016. – Resource access mode: https://www.ti.com/lit/ds/symlink/ads1246.pdf?ts=1631268603884&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FADS1246.

9. ADS1220 datasheet [Electronic resource]. – 2016. – Resource access mode: https://www.ti.com/lit/ds/symlink/ads1220.pdf?ts=1631250599867&ref_url=https%253A%252F%252Fwww.google.ru%252F.
10. Kovtun I. Boiko J., Petrashchuk S., Kałaczyński T. Theory and practice of vibration analysis in electronic packages //MATEC Web of Conferences. – EDP Sciences, 2018. – Т. 182. P. 02015. https://doi.org/10.1051/matecconf/201818202015.
11. Kovtun I.I., Boiko J.M., Petrashchuk S.A. Reliability Improvement of Printed Circuit Boards by Designing Methods for Solder Joint Technical Diagnostics with Application of Acoustic Emission Method //Visnyk NTUU KPI Seriia-Radiotekhnika Radioaparatobuduvannia. – 2019. – №. 79. – P. 60-70. https://doi.org/10.20535/RADAP.2019.79.60-70.
12. Kovtun I., Boiko J., Petrashchuk S., Kałaczyński T. Methods for Vibration Reduction in Enclosed Electronic Packages //MATEC Web of Conferences. – EDP Sciences, 2019. – Vol. 302. – P. 01008. https://doi.org/10.1051/matecconf/201930201008.
13. Chen H. Decision tree support vector machine based on genetic algorithm for multi-class classification / H. Chen, Q. Wang and Y. Shen // Journal of Systems Engineering and Electronics. – 2011. - Vol. 22, №. 2, - P. 322-326. https://doi.org/10.3969/j.issn.1004-4132.2011.02.020.